CODES AND STANDARDS ENHANCEMENT INITIATIVE

2005 Title 24 Building Energy Efficiency Standards Update

CODE CHANGE PROPOSAL FOR

Nonresidential Duct Sealing and Insulation

REPORT JULY 2, 2002

Created on 7/3/02 2:47 PM

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Overview

The substantial opportunity to save energy and peak demand through improvement of ducts under nonresidential Title 24 standards was not recognized and pursued until the AB970 emergency standards process. At that time, a credit similar to that provided for residential duct tightening in the 1998 Standards was introduced into the 2001 Standards for light commercial buildings with ducts installed in unconditioned spaces. The credit was calculated based upon the assumed leakage levels in new residential ductwork. In fact, field data reported on light commercial duct leakage in California indicates that supply duct leakage levels are considerably higher in light commercial systems, and that the return leakage levels could be comparable. The same field verification mechanism was established for tight ducts in light commercial buildings as that for residential ducts, through the use of certified HERS raters.

The focus of the proposal is on light commercial buildings. These buildings are generally served by packaged DX HVAC systems, which cool the majority of the floor space in nonresidential new construction in California, as shown in Figure 1 (AEC, 2001).

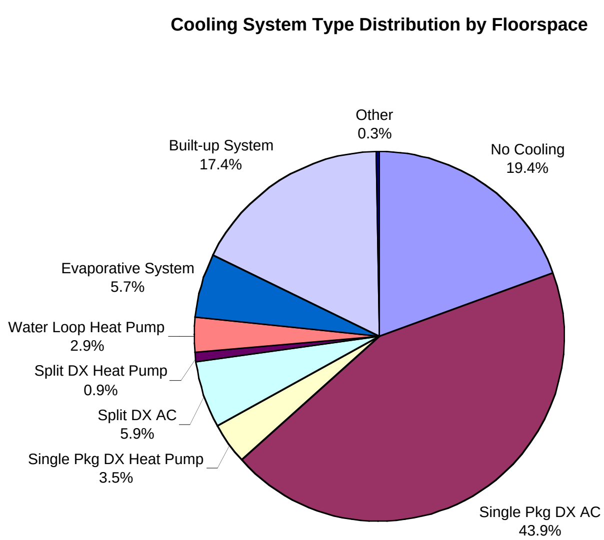

Figure 1. Floor Space Distribution of HVAC Systems in New Commercial Buildings in California.

Within the single package DX air conditioner and heat pump market, systems 20 tons and smaller account for more than 80% of the installed cooling capacity, as shown in Figure 2 (AEC, 2001). At an installed capacity of 250 SF/ton, a 20 ton unit will serve a 5000 SF zone, thus the focus of the Standards on spaces 5000 SF or smaller is well justified.

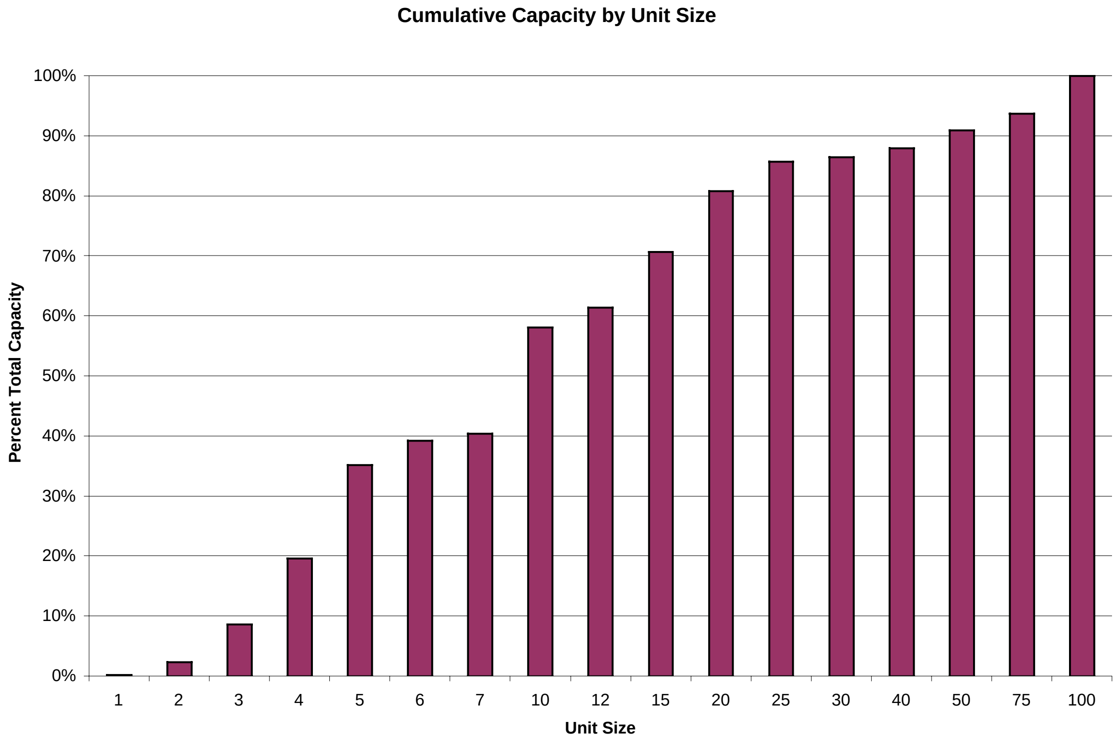

Figure 2. Cumulative Distribution of Single Packaged DX System Size by Installed Capacity (Nominal Tons).

Ductwork in light commercial buildings is generally installed in a "plenum" space between a dropped ceiling and the roof. If the insulation is located on the dropped ceiling (lay-in insulation), with uninsulated plenum walls and roof, the duct systems are located outside the thermal envelope of the building. If the roof and plenum walls are insulated, the ductwork below the roof level is located within the thermal envelope of the building. Ductwork installed above the roof surface is clearly outside of the building thermal envelope. Also, ductwork located in a "plenum" space that is ventilated to the outside (whether insulated at the ceiling or at the roof) is considered outside the building thermal envelope.

Description

This Code Change Proposal updates the treatment of duct systems in light commercial buildings. For any single zone unitary air conditioning system or heat pump serving 5000 SF or less, with duct systems located outside of the thermal envelope of the building, duct leakage sealing will be prescriptively required during installation. Duct insulation R-values are increased from R-4.2 to R-8 for ducts located outside of the thermal envelope.

Benefits

Energy benefits from duct tightening are estimated to be about 20% of the annual cooling consumption in buildings where duct systems are located outside the thermal envelope of the building. Peak demand savings are greater due to higher ambient temperatures during summer peak hours. Comfort in buildings with tight ducts is expected to improve, since the HVAC systems will be better able to serve the loads in the space. In commercial buildings, where the HVAC systems supply continuous ventilation air, leaky and poorly insulated duct systems can actually contribute to warming the space during the cooling season by supplying air that is warmer than room temperature. In this case, duct tightening can improve comfort during building ventilation. Time-dependent valuation (TDV) enhances the cost effectiveness of this measure, since most of the benefits occur during periods of higher energy valuation.

Environmental Impact

No negative environmental impacts are anticipated for this measure.

Type of Change

This code change proposal would make duct tightening a ***prescriptive requirement***. Two options would then be available to the building designer: 1) Require third party verification of duct leakage by an approved provider or 2) Install some other thermal feature or features to provide an energy neutral option that would not require a separate inspection. In the second option, the measure would be evaluated as a part of a performance-based compliance path, where the impacts of non-compliance are traded off for other improvements in the building design.

The proposed change does not change the scope of the standards, since duct tightening was included in the AB 970 proceedings. However, the number of systems affected by this change is greatly expanded. New calculation procedures to address the impacts of duct tightening have been developed, since the techniques used in the AB 970 process were adapted from techniques developed for residential buildings. Changes would apply to the following documents:

- ***Standards*** - to describe the new compliance approach.
- ***ACM*** – to describe the new approach to modeling duct leakage impacts applicable to continuous fan operation and TDV.
- ***Manuals*** **–** similar to changes to the standards, to describe the new compliance approach.
- ***Compliance forms*** – minor changes to reflect differences in testing and sealing procedures.

Technology Measures

Measure Availability and Cost

Equipment and materials to seal duct systems are widely available. Traditional approved materials, such as duct sealing mastic are commonly available. Current requirements for duct leakage testing are outlined in the nonresidential ACM manual. The procedures specified require proficiency in the use of a duct pressurization and flow measurement device, commonly known as a “duct blaster.” These devices are available commercially from several manufacturers, including:

The Energy Conservatory
2801 21st Ave. South
Suite 160
Minneapolis, MN 55407
(612) 827-1117 phone
(612) 827-1051 fax

Retrotec
2200 Queen St., Suite #12
Bellingham, WA. 98226
(360) 738-9835 ext. 308
(360) 647-7724 fax

Infiltec
08 South Delphine Avenue
PO Box 1125

Waynesboro, VA 22980
Phone: (540) 943-2776
Fax: (540) 932-3025

Duct diagnostic and testing services are currently provided by home energy rating system (HERS) raters. Certified HERS raters are trained in the use of duct pressurization and flow measurement devices for duct leakage measurement. Home energy rating services are provided by HERS raters certified by CHEERS (California Home Energy Efficiency Rating System, Inc.), a non-profit organization recognized as a HERS provider by the CEC. Training is provided by CHEERS at locations throughout the state, primarily the PG&E Stockton Training Center, The SCE CTAC facility in Irwindale, the Southern California Gas weatherization training center in Los Angeles, and the SDG&E training center. The CHEERS website lists 240 individuals certified throughout the state to perform Title 24 new construction ratings, including duct diagnostic testing.

Testing of nonresidential HVAC systems is generally done by testing and balancing (T&B) contractors. T&B contractor training and certification is available through the National Environmental Balancing Board (NEBB) and the Association of Air Balance Contractors (AABC). The NEBB has chapters located in Northern California (Oakland) and Southern California (Santa Fe Springs). Their website lists 16 firms certified for T&B services in California, two of which are also certified by CHEERS. THE AABC website lists 9 firms (14 including branch offices). Current practices in the T&B industry promote the use of pitot tube traverses as the primary air flow measurement and duct leakage measurement technique rather than the duct pressurization and flow measurement procedure. Thus, these groups will need to add this technique to their training and certification processes to provide additional capacity for duct diagnostic testing. Although the capacity to test commercial systems on a large scale using the duct pressurization and flow measurement technique is not widely available beyond the HERS rating community, the capability to provide this service will likely grow as the market demand for this service increases.

The costs to seal and test duct systems were derived from residential building studies. The AB 970 residential impact analysis report estimated costs for duct sealing in residential new construction at $250 (CEC, 2000). Nonresidential duct sealing costs for small systems are potentially lower, since access to the duct system during construction is easier than a typical residence; however, since commercial buildings are generally not constructed on a “production” basis, this cost advantage may be offset. For this study, a range of $200 to $300 for a system serving 2000 SF was used ($0.10 - $0.15 per SF) Third party verification costs are estimated at $150 for the same system (PG&E, 2002c), for an additional $0.075 per SF. If a 20% sampling rate for verification is used, the average verification costs drop to $30 per system ($0.015/SF). Based on information received from Owens-Corning Fiberglas, the incremental cost to upgrade duct insulation from R-4.2 to R-8 is estimated at $100 -150 per system. (PG&E, 2002c), or $0.05 - $0.075 per SF.

Useful Life, Persistence and Maintenance

Long term data on the persistence of duct sealing technologies does not currently exist. Properly sealed duct systems should maintain their integrity, provided materials currently approved for use in the Standards are used. The introduction of new leakage sites during routine maintenance of equipment or building remodeling is unknown at this time.

Performance Verification

Performance verification at initial installation of the measure is an integral part of the delivery process. Test equipment is installed to verify that target leakage levels have been achieved. Duct sealing is one of the measures addressed by the Acceptance Requirements for Nonresidential Buildings project (NBI, 2002). Increases in duct leakage levels due to material degradation or introduction of new leakage sites during O&M or remodeling operations will not be addressed by performance verification during initial installation.

Cost Effectiveness

The cost effectiveness of the measure was evaluated using the DOE-2.2 simulation program (see Methodology section below). The net present value of the electricity and gas savings was calculated using the TDV methodology applied to the DOE-2.2 simulation results. The net present value was calculated assuming a 30 year measure life. Total duct sealing costs were estimated at $230 – $450 per system, based on a measure cost range of $200 to $300 per system and a verification cost range of $30 to $150 per system (see Measure Availability and Cost section above). Upgraded duct insulation costs were estimated at $100 - $150 per system.

A series of parametric runs were conducted in conjunction with the nonresidential layin insulation study. A summary of a subset of the results relevant to the duct sealing proposal is shown in the Tables below. The analysis was run for several cases: with and without a "cool" roof, and with and without an air-side economizer to test the sensitivity of the results to the presence of these measures.

Table 1 Duct Sealing Cost Effectiveness Analysis- Standard Roof, No Economizer

Climate Zone	Case	TDV Savings	Measure cost (low)	Benefit / Cost ratio (low)	Measure cost (high)	Benefit / Cost ratio (high)
3	Insulated roof and attic	$331	$230	1.44	$450	0.74
	Insulated ceiling, non-vented attic	$1,641	$230	7.13	$450	3.65
	Insulated ceiling, vented attic	$1,818	$230	7.91	$450	4.04
6	Insulated roof and attic	$489	$230	2.13	$450	1.09
	Insulated ceiling, non-vented attic	$2,032	$230	8.84	$450	4.52
	Insulated ceiling, vented attic	$2,405	$230	10.46	$450	5.35
10	Insulated roof and attic	$553	$230	2.40	$450	1.23
	Insulated ceiling, non-vented attic	$3,335	$230	14.50	$450	7.41
	Insulated ceiling, vented attic	$3,557	$230	15.47	$450	7.91
12	Insulated roof and attic	$442	$230	1.92	$450	0.98
	Insulated ceiling, non-vented attic	$2,615	$230	11.37	$450	5.81
	Insulated ceiling, vented attic	$2,892	$230	12.58	$450	6.43
14	Insulated roof and attic	$576	$230	2.50	$450	1.28
	Insulated ceiling, non-vented attic	$3,339	$230	14.52	$450	7.42
	Insulated ceiling, vented attic	$3,380	$230	14.70	$450	7.51

Assumes sealing R-4.2 ducts to 8% total leakage

Table 2 Duct Sealing Cost Effectiveness Analysis- Cool Roof, No Economizer

Climate Zone	Case	TDV Savings	Measure cost (low)	Benefit / Cost ratio (low)	Measure cost (high)	Benefit / Cost ratio (high)
3	Insulated roof and attic	$314	$230	1.37	$450	0.70
	Insulated ceiling, non-vented attic	$1,071	$230	4.66	$450	2.38
	Insulated ceiling, vented attic	$1,334	$230	5.80	$450	2.96
6	Insulated roof and attic	$436	$230	1.90	$450	0.97
	Insulated ceiling, non-vented attic	$1,314	$230	5.71	$450	2.92
	Insulated ceiling, vented attic	$1,739	$230	7.56	$450	3.86
10	Insulated roof and attic	$523	$230	2.28	$450	1.16
	Insulated ceiling, non-vented attic	$2,404	$230	10.45	$450	5.34
	Insulated ceiling, vented attic	$2,791	$230	12.14	$450	6.20
12	Insulated roof and attic	$412	$230	1.79	$450	0.92
	Insulated ceiling, non-vented attic	$1,982	$230	8.62	$450	4.40
	Insulated ceiling, vented attic	$2,381	$230	10.35	$450	5.29
14	Insulated roof and attic	$556	$230	2.42	$450	1.24
	Insulated ceiling, non-vented attic	$2,463	$230	10.71	$450	5.47
	Insulated ceiling, vented attic	$2,724	$230	11.84	$450	6.05

Assumes sealing R-4.2 ducts to 8% total leakage

Table 3 Duct Sealing Cost Effectiveness Analysis– Standard Roof, With Economizer

Climate Zone	Case	TDV Savings	Measure cost (low)	Benefit / Cost ratio (low)	Measure cost (high)	Benefit / Cost ratio (high)
3	Insulated roof and attic	$255	$230	1.11	$450	0.57
	Insulated ceiling, non-vented attic	$1,313	$230	5.71	$450	2.92
	Insulated ceiling, vented attic	$1,662	$230	7.23	$450	3.69
6	Insulated roof and attic	$429	$230	1.86	$450	0.95
	Insulated ceiling, non-vented attic	$1,701	$230	7.39	$450	3.78
	Insulated ceiling, vented attic	$2,212	$230	9.62	$450	4.91
10	Insulated roof and attic	$503	$230	2.19	$450	1.12
	Insulated ceiling, non-vented attic	$2,869	$230	12.47	$450	6.37
	Insulated ceiling, vented attic	$3,194	$230	13.89	$450	7.10
12	Insulated roof and attic	$336	$230	1.46	$450	0.75
	Insulated ceiling, non-vented attic	$2,031	$230	8.83	$450	4.51
	Insulated ceiling, vented attic	$2,270	$230	9.87	$450	5.05
14	Insulated roof and attic	$425	$230	1.85	$450	0.94
	Insulated ceiling, non-vented attic	$2,774	$230	12.06	$450	6.16
	Insulated ceiling, vented attic	$2,893	$230	12.58	$450	6.43

Assumes sealing R-4.2 ducts to 8% total leakage

Table 4 Duct Sealing Cost Effectiveness Analysis– Cool Roof, With Economizer

Climate Zone	Case	TDV Savings	Measure cost (low)	Benefit / Cost ratio (low)	Measure cost (high)	Benefit / Cost ratio (high)
3	Insulated roof and attic	$290	$230	1.26	$450	0.64
	Insulated ceiling, non-vented attic	$1,153	$230	5.01	$450	2.56
	Insulated ceiling, vented attic	$1,491	$230	6.48	$450	3.31
6	Insulated roof and attic	$454	$230	1.98	$450	1.01
	Insulated ceiling, non-vented attic	$1,382	$230	6.01	$450	3.07
	Insulated ceiling, vented attic	$1,863	$230	8.10	$450	4.14
10	Insulated roof and attic	$514	$230	2.23	$450	1.14
	Insulated ceiling, non-vented attic	$2,289	$230	9.95	$450	5.09
	Insulated ceiling, vented attic	$2,699	$230	11.74	$450	6.00
12	Insulated roof and attic	$341	$230	1.48	$450	0.76
	Insulated ceiling, non-vented attic	$1,619	$230	7.04	$450	3.60
	Insulated ceiling, vented attic	$1,913	$230	8.32	$450	4.25
14	Insulated roof and attic	$431	$230	1.87	$450	0.96
	Insulated ceiling, non-vented attic	$2,238	$230	9.73	$450	4.97
	Insulated ceiling, vented attic	$2,468	$230	10.73	$450	5.48

Assumes sealing R-4.2 ducts to 8% total leakage

This analysis shows that duct sealing is clearly cost effective for duct systems located in unconditioned spaces, and only marginally cost effective for duct systems in conditioned spaces in warm climates at the lower range of cost. Duct sealing is not cost effective at the upper range of cost for duct systems in conditioned space. Economizers and cool roofs affect the savings, but sealing ducts in unconditioned spaces is clearly cost effective under all scenarios examined. The study proposes to require duct sealing for all systems with ducts located outside the thermal envelope.

A similar analysis was done to examine the cost effectiveness of increasing duct insulation resistance from R-4.2 to R-8. The analysis was done on a “sealed” system. A summary of the results is shown in the Tables below:

Table 5. Duct Insulation Upgrade Cost Effectiveness – Standard Roof, No Economizer

Climate Zone	Case	TDV Savings	Measure cost (low)	Benefit / Cost ratio (low)	Measure cost (high)	Benefit / Cost ratio (high)
3	Insulated roof and attic	$63	$100	0.63	$150	0.42
	Insulated ceiling, non-vented attic	$356	$100	3.56	$150	2.38
	Insulated ceiling, vented attic	$300	$100	3.00	$150	2.00
6	Insulated roof and attic	$96	$100	0.96	$150	0.64
	Insulated ceiling, non-vented attic	$441	$100	4.41	$150	2.94
	Insulated ceiling, vented attic	$371	$100	3.71	$150	2.48
10	Insulated roof and attic	$115	$100	1.15	$150	0.77
	Insulated ceiling, non-vented attic	$811	$100	8.11	$150	5.40
	Insulated ceiling, vented attic	$738	$100	7.38	$150	4.92
12	Insulated roof and attic	$88	$100	0.88	$150	0.59
	Insulated ceiling, non-vented attic	$621	$100	6.21	$150	4.14
	Insulated ceiling, vented attic	$581	$100	5.81	$150	3.87
14	Insulated roof and attic	$118	$100	1.18	$150	0.79
	Insulated ceiling, non-vented attic	$865	$100	8.65	$150	5.76
	Insulated ceiling, vented attic	$783	$100	7.83	$150	5.22

Based on upgrading supply duct insulation from R-4.2 to R-8 in a sealed system.

Table 6. Duct Insulation Upgrade Cost Effectiveness – Cool Roof, No Economizer

Climate Zone	Case	TDV Savings	Measure cost (low)	Benefit / Cost ratio (low)	Measure cost (high)	Benefit / Cost ratio (high)
3	Insulated roof and attic	$57	$100	0.57	$150	0.38
	Insulated ceiling, non-vented attic	$204	$100	2.04	$150	1.36
	Insulated ceiling, vented attic	$195	$100	1.95	$150	1.30
6	Insulated roof and attic	$96	$100	0.96	$150	0.64
	Insulated ceiling, non-vented attic	$441	$100	4.41	$150	2.94
	Insulated ceiling, vented attic	$371	$100	3.71	$150	2.48
10	Insulated roof and attic	$101	$100	1.01	$150	0.68
	Insulated ceiling, non-vented attic	$537	$100	5.37	$150	3.58
	Insulated ceiling, vented attic	$531	$100	5.31	$150	3.54
12	Insulated roof and attic	$77	$100	0.77	$150	0.52
	Insulated ceiling, non-vented attic	$435	$100	4.35	$150	2.90
	Insulated ceiling, vented attic	$452	$100	4.52	$150	3.02
14	Insulated roof and attic	$104	$100	1.04	$150	0.70
	Insulated ceiling, non-vented attic	$587	$100	5.87	$150	3.92
	Insulated ceiling, vented attic	$594	$100	5.94	$150	3.96

Based on upgrading supply duct insulation from R-4.2 to R-8 in a sealed system.

Table 7. Duct Insulation Upgrade Cost Effectiveness – Standard Roof, With Economizer

Climate Zone	Case	TDV Savings	Measure cost (low)	Benefit / Cost ratio (low)	Measure cost (high)	Benefit / Cost ratio (high)
3	Insulated roof and attic	$45	$100	0.45	$150	0.30
	Insulated ceiling, non-vented attic	$384	$100	3.84	$150	2.56
	Insulated ceiling, vented attic	$339	$100	3.39	$150	2.26
6	Insulated roof and attic	$85	$100	0.85	$150	0.56
	Insulated ceiling, non-vented attic	$463	$100	4.63	$150	3.09
	Insulated ceiling, vented attic	$400	$100	4.00	$150	2.67
10	Insulated roof and attic	$95	$100	0.95	$150	0.63
	Insulated ceiling, non-vented attic	$783	$100	7.83	$150	5.22
	Insulated ceiling, vented attic	$711	$100	7.11	$150	4.74
12	Insulated roof and attic	$62	$100	0.62	$150	0.41
	Insulated ceiling, non-vented attic	$540	$100	5.40	$150	3.60
	Insulated ceiling, vented attic	$488	$100	4.88	$150	3.25
14	Insulated roof and attic	$90	$100	0.90	$150	0.60
	Insulated ceiling, non-vented attic	$783	$100	7.83	$150	5.22
	Insulated ceiling, vented attic	$709	$100	7.09	$150	4.73

Based on upgrading supply duct insulation from R-4.2 to R-8 in a sealed system.

Table 8. Duct Insulation Upgrade Cost Effectiveness – Cool Roof, With Economizer

Climate Zone	Case	TDV Savings	Measure cost (low)	Benefit / Cost ratio (low)	Measure cost (high)	Benefit / Cost ratio (high)
3	Insulated roof and attic	$39	$100	0.39	$150	0.26
	Insulated ceiling, non-vented attic	$252	$100	2.52	$150	1.68
	Insulated ceiling, vented attic	$256	$100	2.56	$150	1.71
6	Insulated roof and attic	$85	$100	0.85	$150	0.56
	Insulated ceiling, non-vented attic	$463	$100	4.63	$150	3.09
	Insulated ceiling, vented attic	$400	$100	4.00	$150	2.67
10	Insulated roof and attic	$79	$100	0.79	$150	0.53
	Insulated ceiling, non-vented attic	$521	$100	5.21	$150	3.48
	Insulated ceiling, vented attic	$521	$100	5.21	$150	3.47
12	Insulated roof and attic	$52	$100	0.52	$150	0.34
	Insulated ceiling, non-vented attic	$358	$100	3.58	$150	2.39
	Insulated ceiling, vented attic	$357	$100	3.57	$150	2.38
14	Insulated roof and attic	$77	$100	0.77	$150	0.51
	Insulated ceiling, non-vented attic	$541	$100	5.41	$150	3.61
	Insulated ceiling, vented attic	$541	$100	5.41	$150	3.61

Based on upgrading supply duct insulation from R-4.2 to R-8 in a sealed system.

As with duct leakage sealing, upgrading the duct insulation is cost effective in all cases studied where ducts run through an unconditioned space.

Analysis Tools

The AB 970 procedure uses a calculation method derived from ASHRAE Standard 152 to calculate an annual system efficiency multiplier to account for duct leakage effects, and applies this multiplier to annual heating and cooling energy calculated by DOE-2.1E. The current procedure was derived using leakage levels, building loads, and HVAC operating characteristics appropriate for residential buildings. The AB 970 calculation procedures do not specifically address characteristics unique to light commercial buildings, such as continuous fan operation, air-side economizers, higher internal load densities, and daytime-only operation, and do not consider the hourly variations in distribution system efficiency necessary for TDV implementation.

The choice of analysis tools depends largely on the future direction of performance-based compliance. The current compliance tool certified by the Commission is DOE-2.1E, release 110. This version of DOE-2 has the capability to address supply side conduction and leakage losses, and models the interactions between supply side losses and an unconditioned attic. The program, however, assumes supply side leakage is made up from outdoor air, where in most cases, supply side leaks are made up from attic air leaking into the return ducts. DOE-2.2 addresses return side leakage losses, but is not certified by the CEC. EnergyPlus, the next generation simulation tool, does not currently have the capability to model duct leakage.

Given these constraints, the analysis of duct tightening in the context of performance based compliance will consist of the following tools:

1. The current DOE-2.1 E program will be used to calculate electricity and gas consumption data for buildings with perfectly sealed and insulated distribution systems

2. A revised ASHRAE 152 procedure will be used to calculate the seasonal efficiency of duct systems installed in commercial buildings.

3. An hourly duct efficiency modifier will be used to calculate the TDV of duct tightening, similar to the approach taken in residential buildings.

Relationship to Other Measures

Current initiatives concerning lay-in insulation in commercial buildings will influence the overall market potential of this measure. Duct leakage impacts are greatly reduced when the ductwork is located within the conditioned envelope of the building, and this analysis showed that sealing duct systems located within a conditioned space is only marginally cost effective. Cool roof initiatives also impact the effectiveness of this measure, since duct losses are a strong function of the attic temperature, which is impacted by roof absorptivity (PG&E, 2002a). The Acceptance Requirements for Code Compliance initiative (NBI, 2002) addresses some of the delivery and administration issues associated with verifying the effectiveness of duct sealing measures.

Acknowledgments

This project was supported by PG&E through a CASE initiative contract awarded to the Heshong Mahone Group. The author would like to acknowledge Patrick Eilert and Steve Blanc, project managers for PG&E, and Lynn Benningfield, project manager for HMG. This study was prepared by Peter C. Jacobs, Senior Engineer at Architectural Energy Corporation, with major input from Mark Modera (Carrier/Aeroseal) and Jon McHugh (HMG).

The energy modeling aspects of this project were supported by the PIER-funded *Integrated Energy Systems - Productivity and Buildings Science* energy research program managed by the New Buildings Institute. The author would like to also acknowledge Cathy Higgins, Program Director of this project for the New Buildings Institute, Mark Williams, the technical advisor for Element 4 – Small Commercial HVAC, and Don Aumann, the CEC project manager for the NBI PIER project.

Methodology

The approach taken in the AB 970 process was to use a seasonal multiplier on HVAC system efficiency derived from ASHRAE Standard 152. All new Title 24 provisions will be evaluated under a cost-based process using time-dependent valuation (TDV) (PG&E, 2002b). The impact of duct tightening is expected to vary as a function of time and temperature, thus a single value approach will tend to underestimate the impacts under peak conditions. It is necessary to evaluate the impacts of duct tightening on an 8760 hourly basis to fully implement the TDV procedure.

Options for including duct tightening in Title 24 nonresidential compliance were examined by Franconi (CEC, 1999). The work focused on the issues related to modeling duct leakage in DOE-2.1E in large and small commercial buildings, and identified several shortcomings in the program related to duct leakage modeling. Despite these shortcomings, Franconi recommends using DOE-2 as the duct compliance tool based on the key role the program already plays in the nonresidential compliance process. Since the work was published, capabilities to model return side leakage, and the ability to specify the source of the makeup air (either outdoors or a buffer zone containing the duct system) have been added to the DOE-2.2 program. Many of the remaining limitations are more critical for larger buildings with VAV systems that fall outside of the proposed duct sealing standards. A summary of the limitations cited by Franconi, and comments reflecting more recent developments are shown in the Table below:

Table 9. Limitations of DOE-2 for Duct Leakage Modeling

Limitation	Comments
Savings not calculated for re-sizing fans after leakage sealing	Not an issue in small buildings, since fan flows are generally not adjusted.
Leakage makeup air comes from ambient	DOE-2.2 allows specification of a mixture of outdoor and return air as the source of the makeup air
Conduction and leakage losses not modeled for return systems	Return side leakage losses modeled using DOE-2.2; conduction losses are not.
Duct heat loss coefficients are constant, ignoring variations in loss coefficients as a function of air flow, radiation, and duct/ambient delta T.	Limitation still exists, but results are conservative.
Fixed leakage rate assumption	Appropriate for constant volume systems
No explicit link between duct leakage and infiltration	Limitation still exists, but not an issue for balanced supply/return duct leakage or low overall duct leakage levels.

Although DOE-2.2 has sufficient capabilities to model duct leakage in light commercial buildings, the program is not certified by the CEC for compliance. Thus, the approach taken for this project was to use DOE-2.2 as a research tool to investigate the cost effectiveness of duct tightening in nonresidential buildings, and develop a methodology to estimate hourly distribution efficiency that can be applied to DOE-2.1E. The version of the DOE-2.2 program used in this study is “beta041b.”

To estimate the cost effectiveness of duct tightening, a simple “box” prototype model was developed to test the capabilities and evaluate the response of the DOE-2.2 program to several duct efficiency and operating condition assumptions. The eQUEST program was used to develop the basic DOE-2.2 input file. Manual changes were made to the text input file to complete the analysis. A description of the simple box model is shown below:

Table 10 Prototypical Building Model Description

Model Parameter	**Value**
Shape	Rectangular, 50ft x 40ft
Conditioned floor area	2000 SF
Number of floors	1
Floor to ceiling height	9 ft
Plenum height	3 ft
Window/wall ratio	20%
Window type	CTZ 3,6 – Double low e clear (SHGC =0.42; COG U-value = 0.23), CTZ 10,12,14 – Double low e tint (SHGC = 0.37, COG U-value = 0.26)
Exterior wall construction	8 in. concrete tilt-up construction insulated
Ext wall R-Value	CTZ 3,6 R-11 CTZ 10,12,14 – R-13
Infiltration rate	0.3 ACH in occupied zone, varies in attic
Roof construction	Built-up roof over plywood deck
Roof absorptivity and emissivity	Abs = 0.80 (Standard roof) Abs = 0.45 (Cool roof)
Ceiling construction	Acoustic tile
Lighting power density	1.2 W/SF
Equipment power density	0.5 W/SF
Operating schedule	7 am - 6 pm M-F
No. People	11
Outdoor air	15 CFM/person
HVAC system	PSZ
Size	6 ton
CFM	2100 CFM
Sensible Heat Ratio @ ARI conditions	0.7
EER	8.5
Economizer	Fixed OA and outdoor temperature economizers considered
Thermostat setpoints	Heating: 70/55; Cooling: 74/85
Fan power	0.375 W/CFM
Supply duct surface area	27% of floor area, per ACM

Model Parameter	Value
Duct leakage	36% total leakage; evenly split between supply and return (18% supply, 18% return) for leaky case, 8% total leakage for a sealed system
Duct insulation R-value	R-4.2, with an air film resistance of 0.7 added to account for external and internal air film resistance.
Return leak from outside air	0%
Return system type	Ducted

An eQUEST representation of the building is shown in the Figure below:

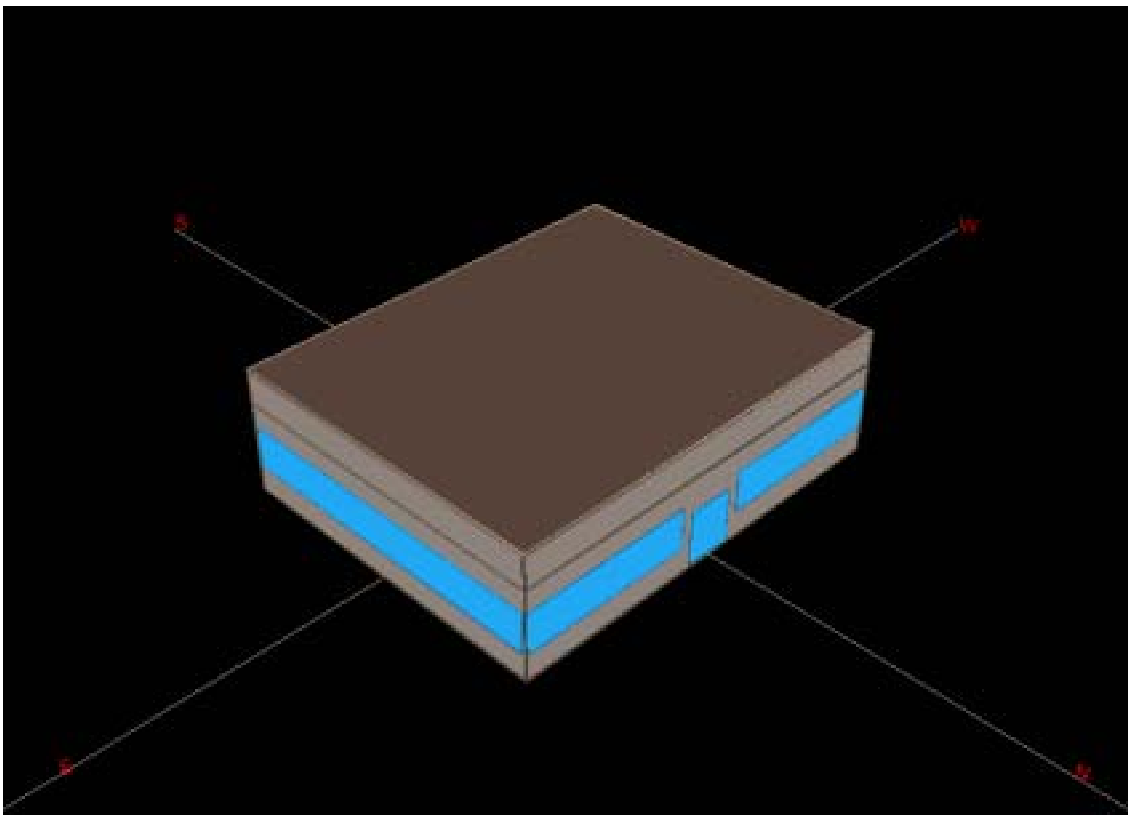

Figure 3. eQUEST representation of prototypical building model

Duct leakage levels were set at 36% total leakage (18% supply, 18% return), based on results from a commercial buildings duct leakage testing and sealing program conducted for Southern California Edison (Modera and Proctor, 2002). These average values are higher than those found in residential studies (22% total leakage).

Results

The implications of operating strategies on distribution system efficiency was investigated by running the model across several representative climate zones, looking at the impact of cycling vs. continuous fans, economizers, and attic space ventilation. The results of these simulations are also compared to the current ASHRAE 152 procedures (assuming 36% total leakage) and the AB 970 values for Case Code 1001 (22% total leakage, R-4.2 duct insulation). These results for two representative climate zones (mild coastal - CTZ03, and hot inland – CTZ12) are shown in the figures below.

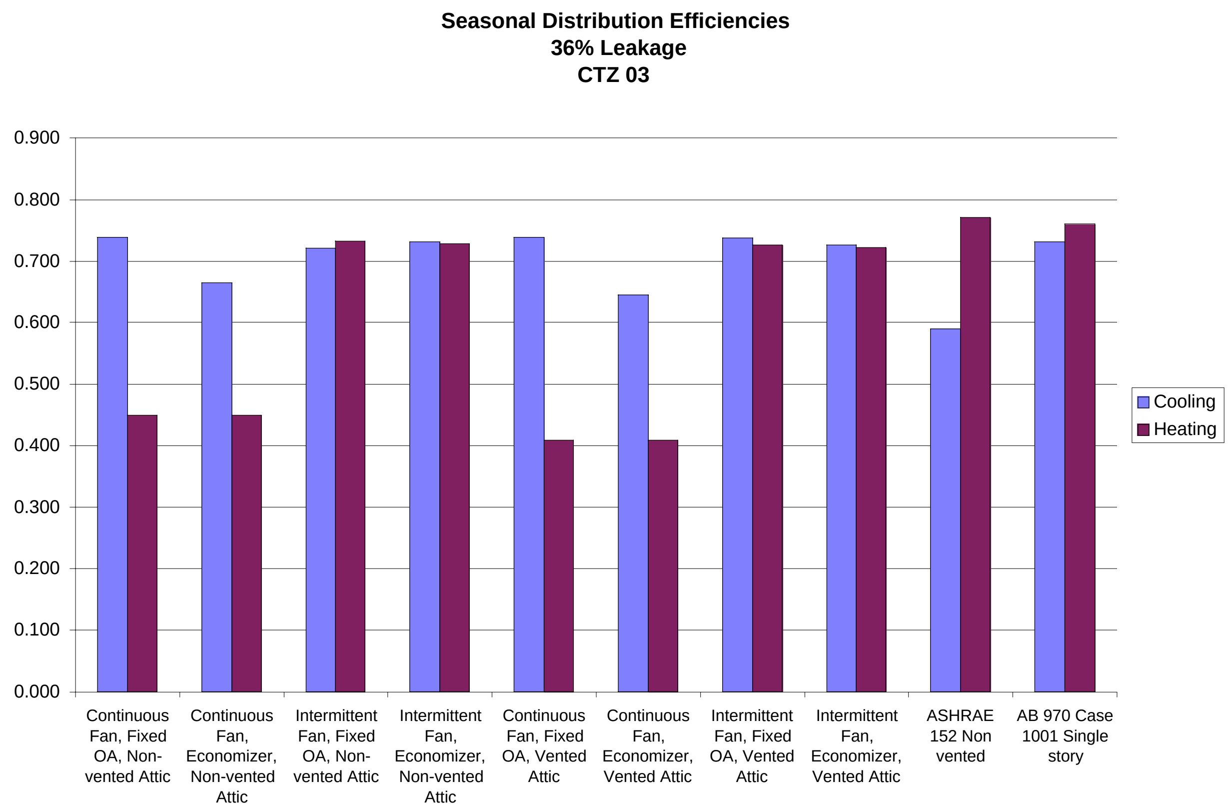

Figure 4. Seasonal distribution efficiency under various operating assumptions, climate zone 3

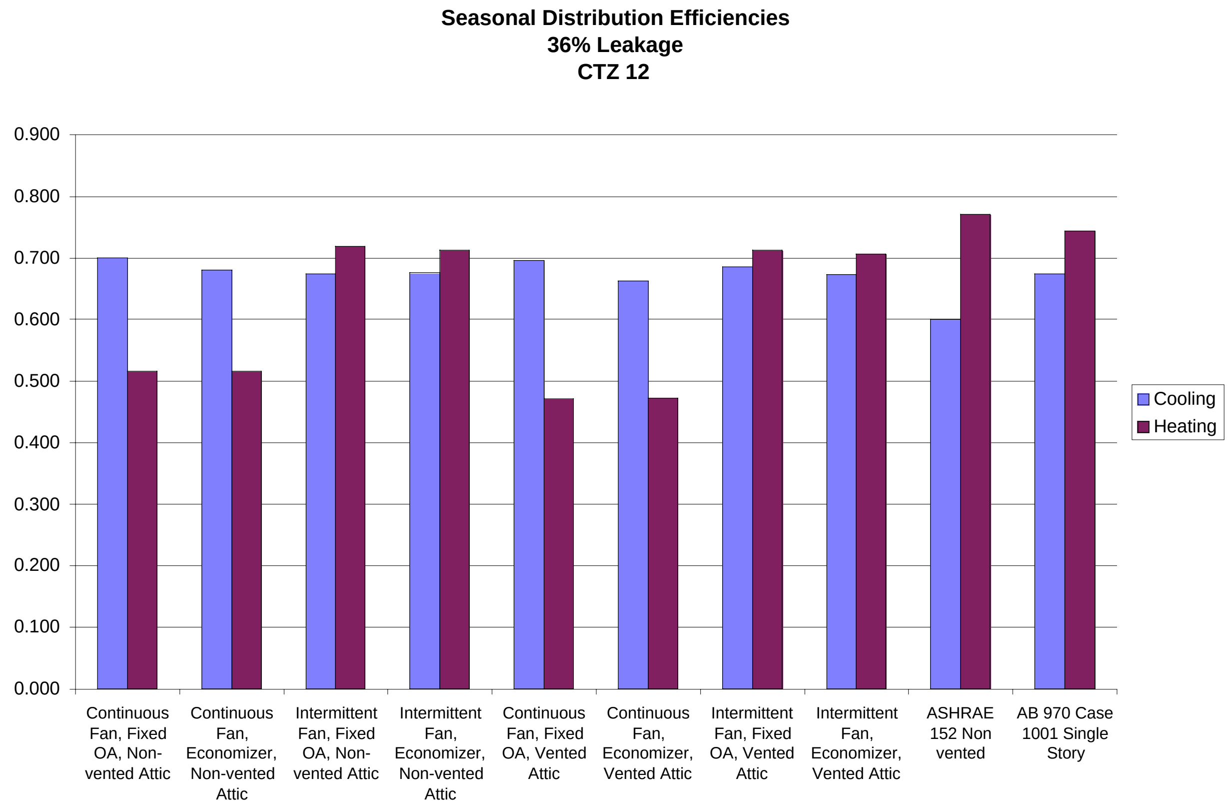

Figure 5. Seasonal distribution efficiency under various operating assumptions, climate zone 12

Several observations based on these results are:

Cooling Distribution Efficiency. The cooling distribution efficiencies calculated by DOE-2 are generally higher than those calculated by the ASHRAE 152 procedure. Since the ASHRAE 152 procedure was developed for residential buildings, it is not surprising that the efficiencies are different. A comparison of the efficiencies predicted by DOE-2 and ASHRAE 152 on a building with residential operation and load density is presented in Appendix A

Heating Distribution Efficiency. The heating distribution efficiencies for the intermittent fan case are quite comparable, but the efficiencies predicted by DOE-2 for the continuous fan case are lower. This is due to the fact that the heating loads are very small in this building, and the duct losses during continuous fan operation represent a significant fraction of the total heating load.

Economizers. The distribution efficiencies generally degrade when economizers are used. This is due to the fact that the attic temperatures during mechanical cooling are higher in systems with economizers. Return side leakage in systems without economizers can actually reduce cooling loads when the attic is cooler than the conditioned space.

Fan mode. Continuous ventilation fan operation (the Title 24 default) can have a dramatic effect on distribution efficiency in the heating mode, especially in mild climates, since the duct system acts as a heat exchanger, thereby adding a significant source of heating load to a building that otherwise requires very little heating energy

Attic ventilation. In general, ventilated attics tend to reduce attic temperatures during cooling operation, improving the duct efficiency. The effect is not particularly dramatic.

To examine the hourly variation in distribution efficiency, simulations of a building with continuous fans operated 8760 hr/yr with and without duct losses were conducted. The distribution efficiencies were normalized to the seasonal average value. Outliers where screened by filtering out hours where the loads were less than 30% of the annual peak load. Results for two representative climate zones are plotted in the following figures:

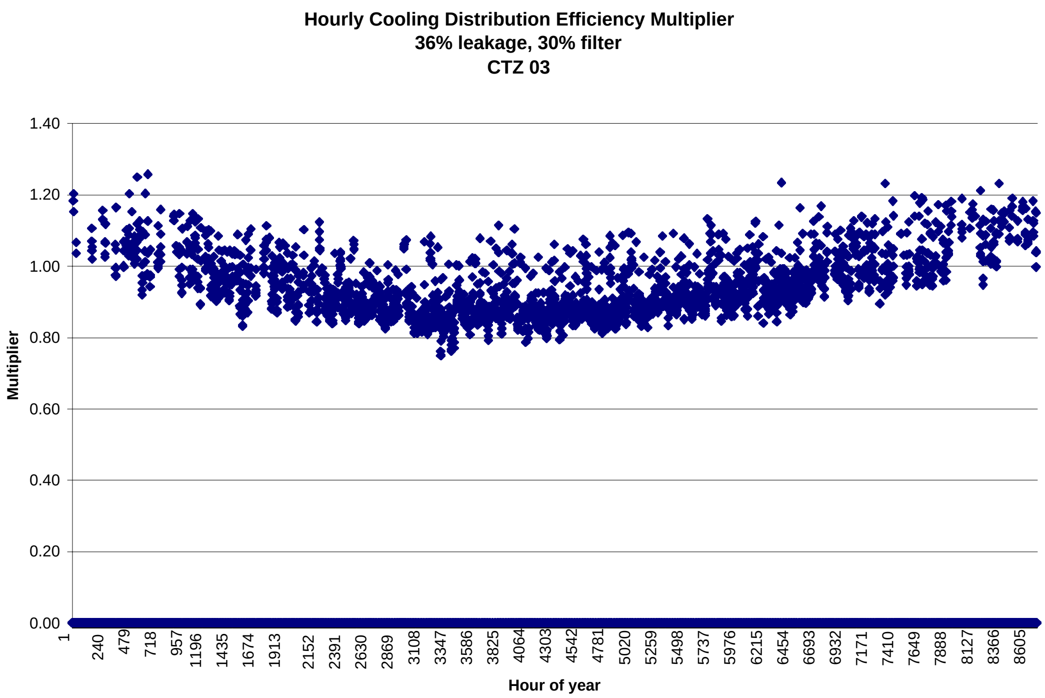

Figure 6 Hourly Cooling Distribution Efficiency Multiplier, Climate Zone 3

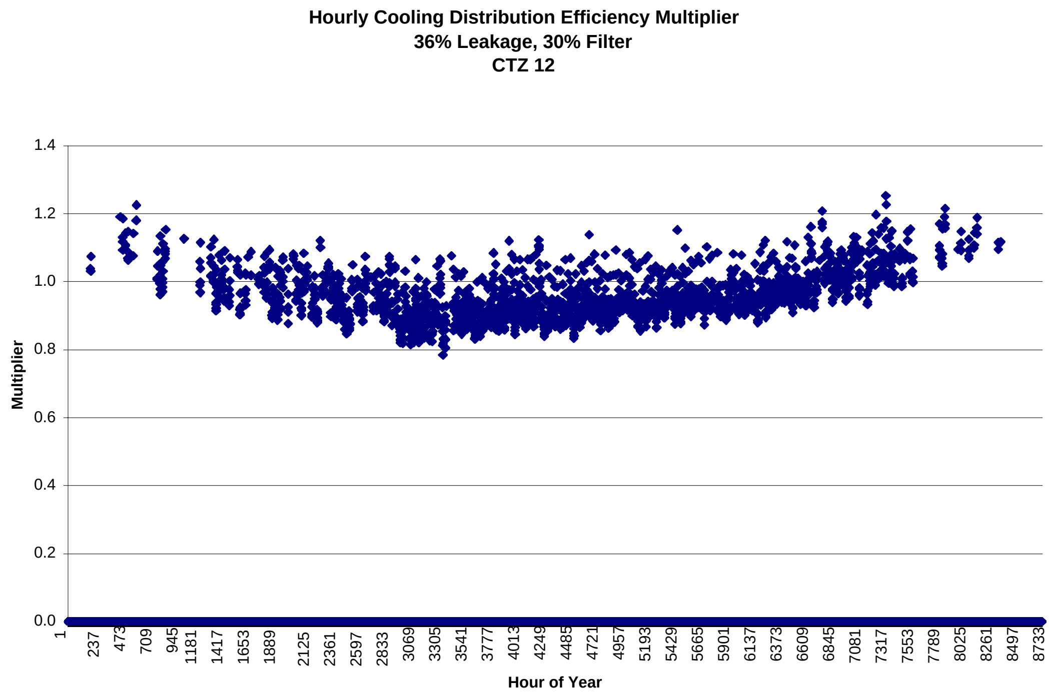

Figure 7 Hourly Cooling Distribution Efficiency Multiplier, Climate Zone 12

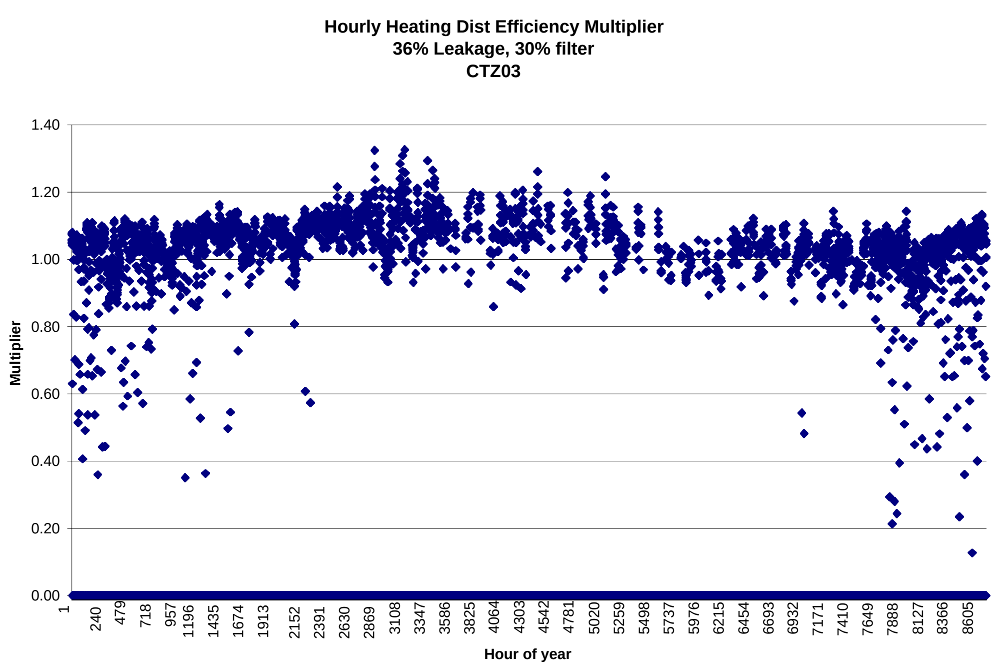

Figure 8 Hourly Heating Distribution Efficiency Multiplier, Climate Zone 3

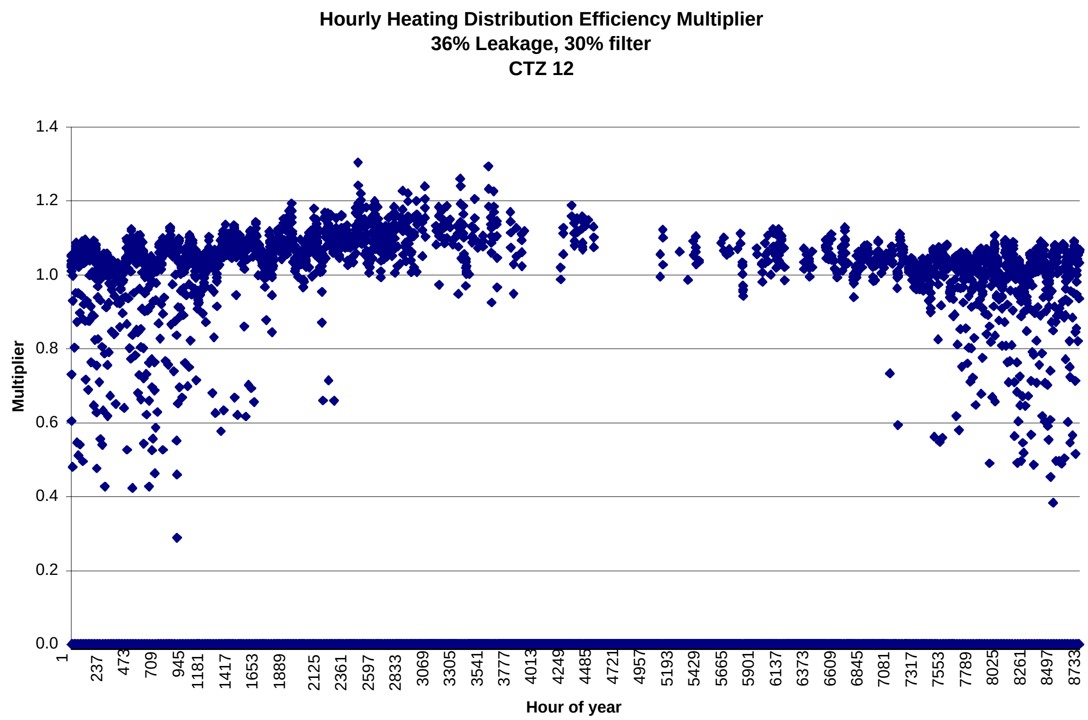

Figure 9 Hourly Heating Distribution Efficiency Multiplier, Climate Zone 12

The cooling distribution efficiency plots show both diurnal and seasonal variations on the order of ±20% in both climate regions. The heating distribution efficiency plots show a similar variation, with several points at very low efficiencies. The low values correspond to very low hourly heating loads, where the distribution losses are a significant fraction of the total heating load.

Recommendations

Based on this analysis, we propose the following changes to the Standards:

1. Establish a prescriptive requirement for duct leakage sealing for all single zone unitary systems serving spaces 5000 SF or less, where ducts are located outside the building thermal envelope.

2. Establish a prescriptive requirement for R-8 duct insulation for all systems with ducts located outside the building thermal envelope.

Proposed Standards Language

The following changes to the Standards Language are proposed:

Revise Section 124(a) as follows:

(a) **CMC Compliance**. All air distribution system ducts and plenums, including, but not limited to, building cavities, mechanical closets, air-handler boxes and support platforms used as ducts or plenums, shall be installed, sealed and insulated to meet the requirements of the 1998 CMC Sections 601, 603, 604, and Standard 6-3, incorporated herein by reference. Portions conveying conditioned air shall either be insulated to a minimum installed level of R-~~4.2~~ 8.0 (or any higher level required by CMC Section 604) or be enclosed entirely in conditioned space. Connections of metal ducts and the inner core of flexible ducts shall be mechanically fastened. Openings shall be sealed with mastic, tape, aerosol sealant, or other duct-closure system that meets the applicable requirements of UL 181, UL 181A, or UL 181B. If mastic or tape is used to seal openings greater than 1/4 inch, the combination of mastic and either mesh or tape shall be used.

EXCEPTION 1 TO Section 124(a): Duct systems located in unconditioned spaces within the thermal envelope of the building shall be insulated to a minimum installed level of R-4.2 (or any higher level required by CMC Section 604).

Add Section 144(i) as follows:

(i) Air Distribution System Duct Leakage Sealing.

1. All duct systems shall be sealed to a leakage rate not to exceed 6% of the total measured fan flow, as confirmed through field verification and diagnostic testing, in accordance with procedures set forth in the Nonresidential ACM Manual.

EXCEPTION to Section 144 (i): Variable air volume (VAV) systems and non-unitary air-conditioners and heat pumps serving areas greater than 5,000 square feet.

Reason

This proposed change requires duct sealing and testing on all duct systems. It also uses the established testing procedure to provide for certification and field verification of minimum duct leakage.

Proposed ACM Language

2.4.2.7 Cooling Efficiency of DOE Covered Air Conditioners

Description: ACMs must require the user to input the SEER (seasonal energy efficiency ratio) of any DOE-covered consumer product. ACMs must allow the user to input the EER (energy efficiency ratio), however the ACM must not require this input for HVAC equipment that is covered by the U.S. DOE appliance standards.

ACMs must also use the ARI net cooling capacity input by the user, as required by this chapter, and the ARI tested fan power and part load capacity as calculated according to this chapter. These three values are also necessary to model efficiency of DOE-covered consumer products.

Modeling of SEER is achieved through accounting for the Electrical Input Ratio, EIR, and total system cooling capacity as functions of Outside Dry-Bulb (ODB) and Coil Entering Wet-Bulb (WB) temperatures, and through accounting for duct efficiency impacts on EIR.

The reference method is based on a created performance curve, similar to the DOE 2.1 curve COOL-EIR-FT, using the following points for WB, ODB and N_{eir}, respectively. This new curve is given below in terms of the reference computer program curve-fit instruction. For single-zone systems with ducts ~~in buffer spaces~~ located outside the thermal envelope~~for which the verified sealed duct option has been elected~~, the COOL-EIR-SEER shall be divided by the seasonal distribution efficiency calculated with Equation 4.17 in Appendix G.

COOL-EIR-SEER = CURVE-FIT
TYPE = BI-QUADRATIC
DATA = (67,95,1.0)
(67,82,N_{eirb})
(67,110,1.174)
(67,105,1.113)
(67,70,$N_{eir70/67adj}$)
(80,95,0.897)
(50,95,1.070) ..

where N_{eirb} and $N_{eir70/67adj}$ are calculated as follows:

1. ACMs must first calculate an EER_b from the following equation:

$$EER_b = \frac{SEER}{1 - 0.5 \times C_d}$$

Equation 2.4.1

Where:

EER_b = Energy Efficiency Ratio at DOE part-load conditions. [Btuh/watt]

C_d = Cyclical degradation coefficient at DOE part-load Conditions

2. If the EER is not input, calculate EER from the following equation:

$$EER = 0.855 \times EER_b$$

Equation 2.4.2

3. Calculate the electrical input ratio, EIR_a, at ARI conditions according to the following equation:

$$EIR_a = \frac{(CAP_a / EER) - ARIFanPower}{(CAP_a / 3.413) + ARIFanPower}$$

Equation 2.4.3

ARI Fan Power = The power [watts] used by the supply fan for the purpose of performing ARI, CEC and DOE approved tests (See ***ARI Fan Power***.)

CAP_a = The net cooling capacity at ARI conditions of 95 outside dry-bulb(ODB) and 67 coil entering wet-bulb (WB) [Btuh]

4. Calculate the electrical input ratio, EIR_b, at ARI part-load conditions according to the following equation:

$$EIR_b = \frac{(CAP_b / EER_b) - ARIFanPower}{(CAP_b / 3.413) + ARIFanPower}$$

Equation 2.4.4

Where:

EER_b = From Equation 2.4.1 above. [Btuh/watts]

EIR_b = The electrical input ratio [unitless], or cooling electrical efficiency of the piece of equipment at ARI part-load conditions

CAP_b = The net cooling capacity [Btuh] at ARI part-load conditions (82 ODB and 67 WB), given by the following equation:

$$CAP_b = 1.07 \times CAP_a$$

Equation 2.4.5

Where

CAP_a= The net cooling capacity [Btuh] at ARI conditions of 95 outside dry-bulb (ODB) and 67 coil entering wet-bulb (WB)

5. Normalize EIR_b based on ARI conditions, 95 outside dry-bulb (ODB):

$N_{eirb} = EIR_b/EIR_a$ [unitless]

6. Calculate $N_{eir70/67adj}$ according to the following equation:

$N_{eir70/67adj} = 0.876 \times N_{eirb}$ [unitless]

For heat pumps, the reference method uses performance curves based on the ratio of the COPs and CAPACITIES at 47°F and at 17°F (COP_{47}, COP_{17}, CAP_{47}, CAP_{17}) and creates new performance curves, similar to the DOE 2.1 COOL-

EIR-FT and COOL-CAP-FT, using the following points for ODB and the COPs and CAPACITIES at these temperatures. For single-zone systems with ducts ~~in buffer spaces~~ located outside the thermal envelope ~~for which the verified sealed duct option has been elected~~, the HP-EIR-FT shall be divided by the seasonal distribution efficiencies calculated with Equation 4.17 in Appendix G for both the standard and proposed building.

HP-EIR-FT = CURVE-FIT
TYPE = CUBIC
DATA =(67,0.856)
(57,0.919)
(47,1.000)
(17,COP_{47}/COP_{17})
(7,1.266×COP_{47}/COP_{17})
(-13, 3.428) ..

HP-CAP-FT = CURVE-FIT
TYPE = CUBIC
DATA =(67,1.337)
(57,1.175)
(47,1.000)
(17,CAP_{17}/CAP_{47})
(7,0.702×CAP_{17}/CAP_{47})
(-13, 0.153) ..

DOE Keyword: COOLING-EIR

Input Type: Default

Tradeoffs: Yes

Modeling Rules for Proposed Design: ACMs shall require users to input a value for SEER and shall allow users to input a value for EER. ACMs shall use 0.03 for the cyclical degradation coefficient C_d. The reference method uses user input values to generate the required performance curves for the proposed design.

Default: Minimum SEER and EER as specified in the Appliance Efficiency Regulations

Modeling Rules for Reference Design (New): The ACM shall assign standard design performance data for the above functions according to the following criteria:

a) If the proposed design system is a *single package* unit according to the CEC Appliance Efficiency Standards, the standard design shall use an EER of 8.6, an SEER of 9.9 and a C_d of 0.03 to develop the required performance curves.

b) If the proposed design system is a *split system* according to the CEC Appliance Efficiency Standards, the standard design shall use an EER of 8.7, an SEER of 10.0 and a C_d of 0.03 to develop the required performance curves.

Modeling Rules for Reference Design (Existing Unchanged The ACM shall assign standard design performance data for the above functions according to the following criteria:

& Altered Existing):

a) If the existing system is a *single package* unit according to the CEC Appliance Efficiency Standards, the standard design shall use the EER or the SEER of the existing system and a C_d of 0.03 to develop the required performance curves.

b) If the existing system is a *split system* according to the CEC Appliance Efficiency Standards, the standard design shall use the EER or the SEER of the existing system and a C_d of 0.03 to develop the required performance curves.

The ACM shall use the ARI fan power of the existing system.

2.4.2.8 Cooling Efficiency of Packaged Equipment not Covered by DOE Appliance Standards

Description: ACMs shall require the user to input the EER for all packaged cooling equipment that are not covered by DOE appliance standards.

ACMs shall also require the user to input the net cooling capacity, CAPa, at ARI conditions for all cooling equipment.

For equipment where supply fan energy is included in the calculation of EER and CAPa, the reference method shall calculate the electrical input ratio, EIR, according to Equation 2.4.4.
For single-zone systems with ducts ~~in buffer spaces~~ located outside the thermal envelope~~for which the verified sealed duct option has been elected~~, the COOL-EIR shall be divided by the seasonal distribution efficiencies calculated with Equation 4.17 in Appendix G for both the standard and proposed building.

DOE Keyword: COOLING-EIR

Input Type: Default

Tradeoffs: Yes

Modeling Rules for Proposed Design: The ACM shall require the user to input efficiency descriptors at ARI conditions for all equipment documented in the plans and specifications for the building.

Default: Minimum EER as specified in the Appliance Efficiency Regulations

Modeling Rules for Reference Design (New): For the reference method, the standard design shall assign the EER and EIR of each unit according to the applicable requirements of the Appliance Efficiency Standards or the Standards. The EIR of the equipment will be based on the proposed system with an EER that meets the applicable requirements of the Standards but has the same cooling capacity and ARI fan power as the unit selected for the proposed design.

Modeling Rules for Reference Design (Existing Unchanged & Altered Existing): ACMs shall use the EER, EIR, and the ARI fan power of the existing system. The EIR of the existing equipment must be based on the EER and the ARI fan power of the existing system.

2.4.2.10 Heating Efficiency of DOE Covered Heat Pumps

Description: ACMs must require the user to input: (1) the Heating Seasonal Performance Factor (HSPF); (2) the heating capacity at 47 ODB; and, (3) the system configuration, either *single package* unit or *split system* for DOE covered heat pumps.

The reference method calculates an equivalent Coefficient Of Performance (COP) according to the following:

a) For *single package* units:

$$COP = \left(0.2778 \times HSPF + 0.9667\right)$$

Equation 2.4.6a

b) For *split systems*:

$$COP = \left(0.4813 \times HSPF - 0.2606\right)$$

Equation 2.4.6b

The reference method will calculate the total heating capacity at ARI conditions, $HCAP_{atot}$ of the heat pump according to the following equation:

$$HCAP_{atot} = HCAP_{a} - \left(3.413 \times ARIFanPower\right)$$

Equation 2.4.7

where the total capacity, $HCAP_{atot}$ is given in Btu per hour [Btuh] and ARIFanPower is rated in watts.

The reference method calculates the electrical heating input ratio, HIR, according to the following equation:

$$HIR = \frac{[HCAP_{a} / (COP \times 3.413)] - ARIFanPower}{(HCAP_{a} / 3.413) - ARIFanPower}$$

Equation 2.4.8

For single-zone systems with ducts ~~in buffer spaces~~ located outside the thermal envelope~~for which the verified sealed duct option has been elected,~~ the HEATING-EIR shall be divided by the seasonal distribution efficiencies calculated with Equation 4.17 in Appendix G for both the standard and proposed building.

DOE Keyword: HEATING-HIR

Input Type: Default

Tradeoffs: Yes

Modeling Rules for Proposed Design: The ACM shall require the user to input all required data, as it occurs in the construction documents.

Default: Minimum COP as specified in the Appliance Efficiency Regulations

Modeling Rules for Reference Design (New): The reference method and all ACMs shall assign a COP of 2.8 to standard design *single package* units and 3.0 to standard design *split systems*.

Modeling Rules for Reference Design (Existing Unchanged & Altered Existing): ACMs shall use the COP and the ARI fan power of the existing system.

2.4.2.11 Heating Efficiency of Heat Pumps not Covered by DOE Standards

Description: ACMs shall require the user to input the COP for all packaged heat pump equipment with fans that are not covered by DOE appliance standards.

ACMs shall also require the user to input the net heating capacity, $HCAP_a$, at ARI conditions for all equipment.

The reference method calculates the electrical heating input ratio, HIR, according Equation 2.4.8.
For single-zone systems with ducts ~~in buffer spaces~~ located outside the thermal envelope~~for which the verified sealed duct option has been elected~~, the HEATING-EIR shall be divided by the seasonal distribution efficiencies calculated with Equation 4.17 in Appendix G for both the standard and proposed building.

DOE Keyword: HEATING-HIR

Input Type: Default

Tradeoffs: Yes

Modeling Rules for Proposed Design: The ACM shall require the user to input efficiency descriptors as they occur in the construction documents.

Default: Minimum COP as specified in the Appliance Efficiency Regulations

Modeling Rules for Reference Design (New): For the reference method, the HIR of each unit in the standard design is determined according to the applicable requirements of the Appliance Efficiency Standards or the Standards.

Modeling Rules for Reference Design (Existing Unchanged & Altered Existing): ACMs shall determine the HIR of each existing system using the COP and the ARI fan power of the existing system.

2.4.2.12 Heating Efficiency of DOE Covered Fan Type Central Furnaces

Description: ACMs shall require the user to input: (1) the AFUE; (2) the heating capacity; and (3) the system configuration for all DOE covered fan type central furnaces.

The reference method calculates an equivalent heating input ratio, HIR, according to the following:

a) For *single package* units:

$$HIR = (0.005163 \times AFUE + 0.4033)^{-1}$$

Equation 2.4.9a

b) For *split systems* with AFUEs not greater than 83.5:

$$HIR = (0.002907 \times AFUE + 0.5787)^{-1}$$

Equation 2.4.9b

c) For *split systems* with AFUEs greater than 83.5:

$$HIR = (0.011116 \times AFUE - 0.098185)^{-1}$$

Equation 2.4.9c

For single-zone systems with ducts ~~in buffer spaces~~ located outside the thermal envelope~~for which the verified sealed duct option has been elected~~, the HEATING-EIR shall be divided by the seasonal efficiencies calculated with Equation 4.17 in Appendix G for both the standard and proposed building.

DOE Keyword: HEATING-HIR

Input Type: Default

Tradeoffs: Yes

Modeling Rules for Proposed Design: ACMs shall require the user to input the AFUE of each DOE covered central furnace.

Default: Minimum AFUE as specified in the Appliance Efficiency Regulations

Modeling Rules for Reference Design (New): The reference method assigns an HIR of 1.24 to all standard design heating systems when a fan-type central furnace is the proposed heating system.

Modeling Rules for Reference Design (Existing Unchanged & Altered Existing): ACMs shall determine the HIR of each existing system using the AFUE of the existing system.

2.4.2.13 Heating Efficiency Fan Type Central Furnaces not Covered by DOE Standards

Description: The ACM shall require the user to input the steady state efficiency, or the HIR, of each furnace for each furnace's rated capacity.

For single-zone systems with ducts ~~in buffer spaces~~ located outside the thermal envelope~~for which the verified sealed duct option has been elected~~, the HEATING-EIR shall be divided by the seasonal distribution efficiencies calculated with Equation 4.17 in Appendix G for both the standard and proposed building.

DOE Keyword: HEATING-HIR

Input Type: Default

Tradeoffs: Yes

Modeling Rules for Proposed Design: The ACM shall require the user to input efficiency descriptors as they occur in the construction documents.

Default: Minimum COP as specified in the Appliance Efficiency Regulations

Modeling Rules for Reference Design (New): The standard design shall assign the HIR of each unit according to the applicable requirements of the Standards.

Modeling Rules for Reference Design (Existing Unchanged & Altered Existing): ACMs shall determine the HIR of each existing system using the AFUE of the existing system.

2.4.2.35 HVAC Distribution Efficiency of Packaged Equipment

Description: ACMs shall be able to determine the efficiency of ducts in the unconditioned spaces between insulated ceilings and roofs.

ACMs shall require the user to enter the duct insulation R-value, the number of building stories, and whether or not the ducts will be sealed and tested for reduced duct leakage.

ACMs shall be able to reproduce the duct efficiencies in Appendix H

DOE Keyword: None. Duct efficiency divisors for COOLING-EIR, COOLING-EIR-SEER and HEATING-HIR will be calculated by means of the equations in Appendix G.

Input Type:	Default
Tradeoffs:	Yes
Modeling Rules for Proposed Design:	The ACM shall require the user to input duct R-value, the number of building stories and whether or not credit for reduced duct leakage will be claimed and tested.
Default:	Duct R-value of 4.2 [h°F ft^2/Btu] and duct leakage of ~~28~~ 36% of fan flow. Number of stories is defaulted to one (1).
Modeling Rules for Reference Design (New):	The Reference Design shall assume the default values for the duct efficiency inputs (Duct R-value = ~~4.2~~ 8, Duct Leakage = ~~6~~ 8%) except that the number of stories shall be the same as for the Proposed Design.
Modeling Rules for Reference Design (Existing Unchanged & Altered Existing):	Applies only if system serves 5000 SF or less, and has ductwork outside thermal envelope. ACMs shall model the same distribution system for the Reference Design as for the Proposed Design

Changes to Chapter 7: Non-Residential Duct Installation Verification And Diagnostic Testing Using Home Energy Rating Systems (HERS)

1. Insulation level of ducts [R 4.2] to [R-8] for ducts outside thermal envelope

2. The leakage level of the duct system [36% of fan flow]. Two values are possible: the default or 8% of fan flow if measured and verified at no more than 6% of fan flow.

Changes to Appendix G: Standard Procedure for Determining the Seasonal Energy Efficiencies of Single-Zone Non-Residential Air Distribution Systems in the Space Between an Insulated Ceiling and the Roof

Sections 4.3 through 4.5 shall be modified to predict seasonal distribution systems efficiencies of non-residential buildings.

4.3.4 Duct Location

Ducts shall be considered to be installed in spaces between ceilings and roofs or building exteriors if more than ~~50~~ 20 lineal feet of duct or 75 percent of the duct surface area is outside the building envelope, and that the space is either a) vented to the outdoors, and/or b) outside the building insulation.

4.3.8 Duct Leakage

4.3.8.1 Duct Leakage Factor for Delivery Effectiveness Calculations

Default duct leakage factors shall be obtained from Table 4.3, using the “not Tested” values.

Duct leakage factors shown in Table 4.3 shall be used in calculations of delivery effectiveness.

Table 4.3 Duct Leakage Factors		
	Duct Leakage Diagnostic Test Performed using Section 4.3.8.2 Procedures	$a_s = a_r =$
Duct systems in buildings built prior to 2001	Not tested	~~0.86~~ 0.82
Duct systems in buildings built after 2001	Not tested	0.82
Duct systems in buildings of all ages, System tested after HVAC system completion	(Q_{25}) Total leakage is less than 0.06 Q_e	0.96

Changes to Appendix H – Seasonal Energy Efficiencies for Air Distribution Systems

Appendix H values shall be calculated using the duct efficiency equations from Appendix G.

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Appendix A: Validation of DOE-2.2 Duct Leakage Modeling Procedures.

To investigate the validity of the DOE-2.2 duct loss modeling process, a limited set of simulations were done. These simulations were conducted to verify the general capabilities of the program, and identify gross problems or bugs in the algorithms.

Attic Energy Balance

A design-day sequence of two weeks of constant weather data input was derived to achieve a steady-state response of the building to the environment. An energy balance was calculated for the attic space, to check the interactions between duct losses and the attic space temperature. The results of the exercise are summarized in the Figure below.

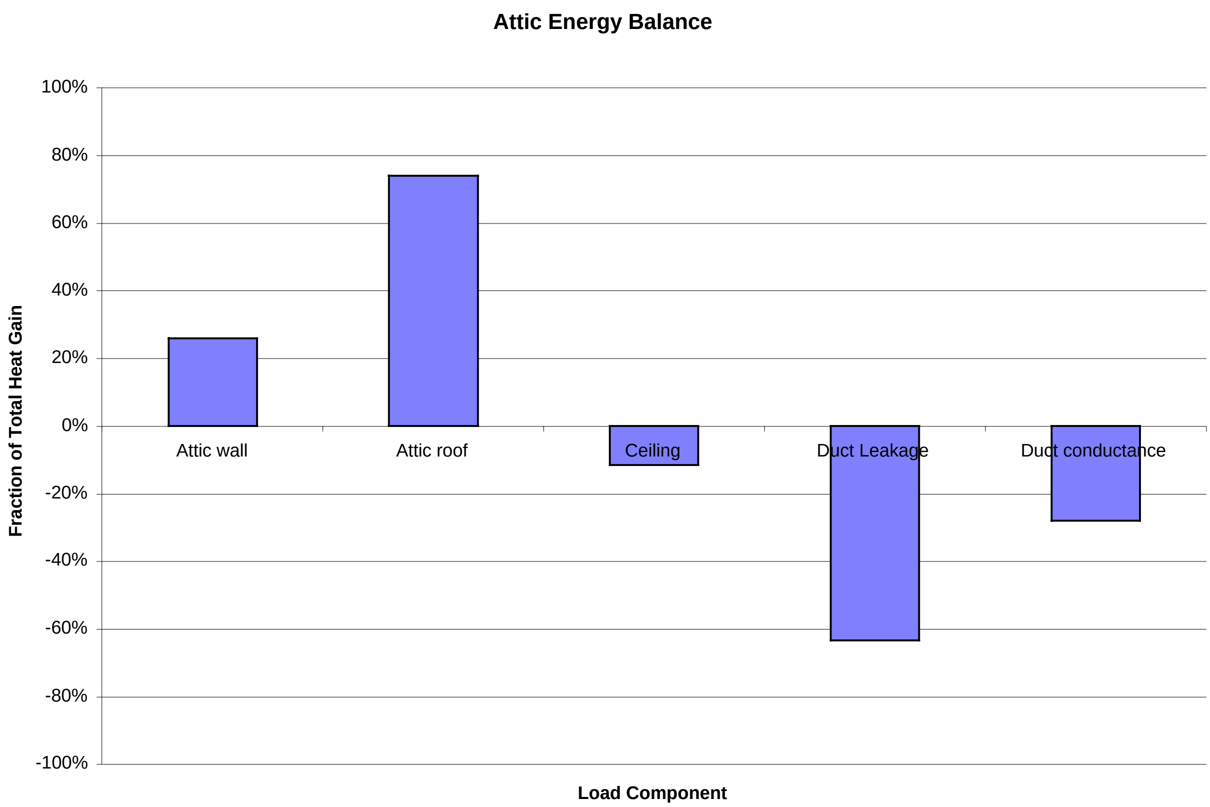

Figure A-1. Attic Energy Balance

Heat gains through the attic walls and roof are balanced by losses through the ceiling to the conditioned space and the cooling effect provided by supply side duct leakage and conduction losses. The attic energy balance closed to within 2%.

Duct Loss and Gain Calculations

Another comparison was done to verify the supply duct heat gain algorithms. Hourly heat gains were calculated based on simulated attic and duct temperatures, and compared to the hourly values reported by DOE-2 as shown below:

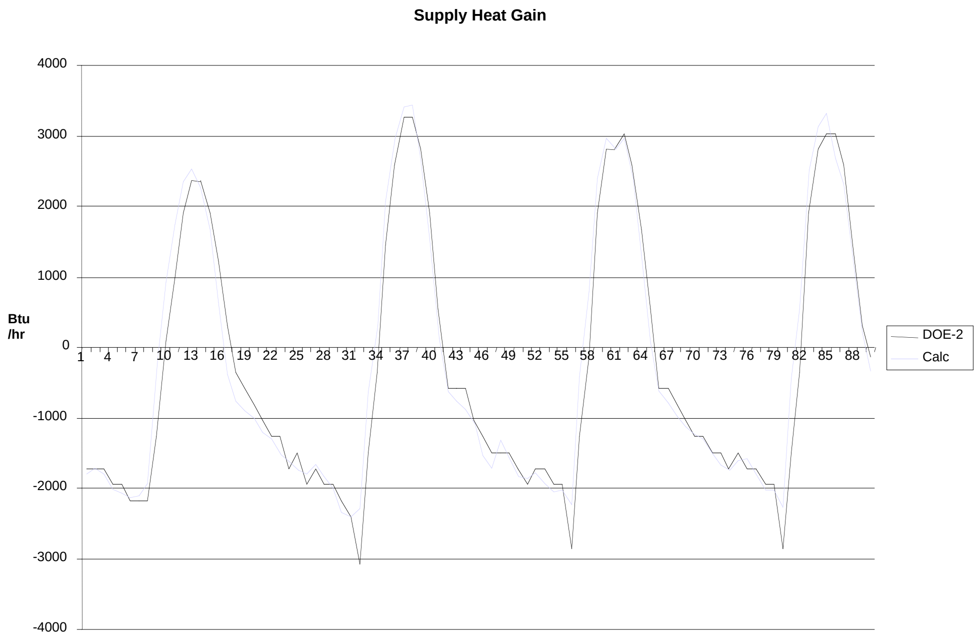

Figure A-2 Supply Heat Gain Comparison

Note, the simulated data track the calculated values closely for most hours. This comparison shows a time lag in the calculated vs. simulated losses near system start/stop transition hours. Since DOE-2 does not attempt to iterate on the systems energy balance at each time step, it sometimes takes a time step or two for the calculations to converge.

A comparison of the simulated and calculated return air temperatures was done to confirm the return side air leakage calculations. The results of this comparison for a typical summer and winter day sequence are shown below:

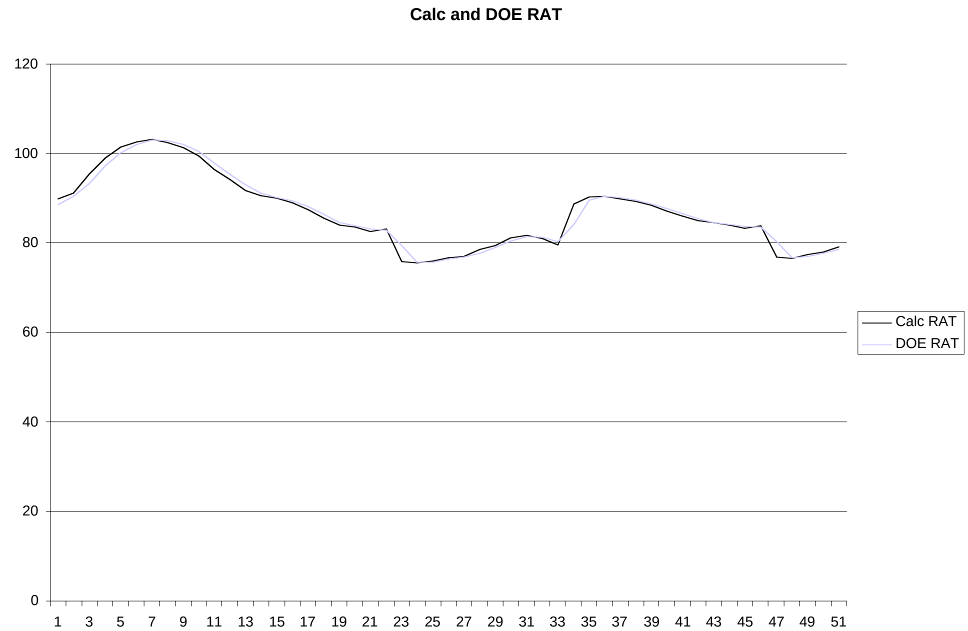

Figure A-3 Return Air Temperature Comparison, Cooling Day

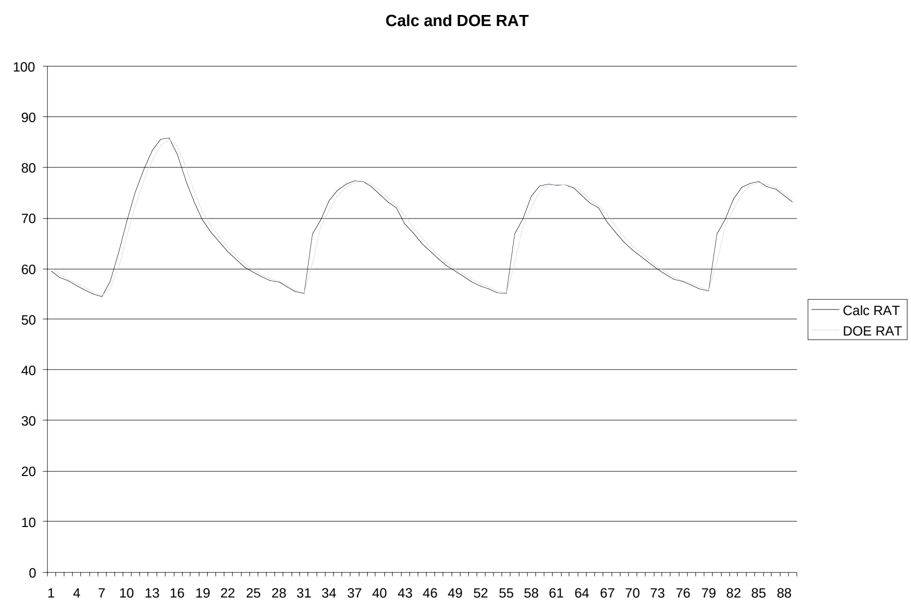

Figure A-4 Return Air Temperature Comparison, Heating Day

The calculated and simulated return air temperatures track quite well. An initial investigation into return side losses exposed a bug in the DOE-2.2 code, which was reported and promptly fixed by the code developers, resulting in release beta 42b of the DOE-2.2 program.

Moisture Balance

An additional investigation into the modeling of moisture effects in the plenum and return air system was conducted. Hourly data were examined for a period with high ambient humidity. The plenum humidity is not tracked by DOE-2 as an explicit hourly report variable, but was calculated from a moisture balance on the return air systems and a moisture balance on the plenum. For this analysis, infiltration and internal moisture generation was set to zero, thus the room humidity ratio is equal to the supply humidity ratio. The results of this exercise is shown in the figure below:

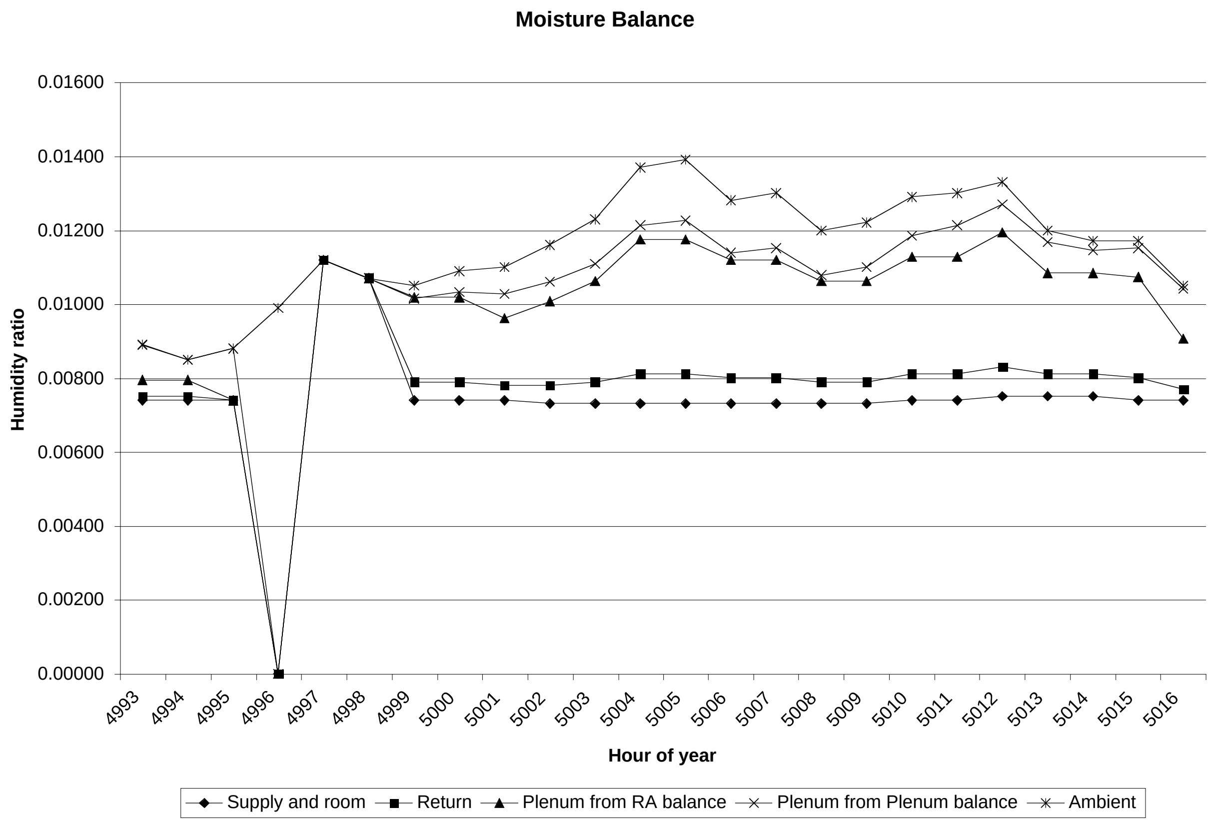

Figure A-5 Moisture Balance Calculation

The attic humidity calculated from both methods track fairly closely. Attic humidity is less than the ambient humidity, showing the dehumidification effect of supply side leakage. Return humidity is greater than zone humidity, showing the additional latent load imposed by return side leakage.

Hourly Model Response

Hourly data sequences for the building peak cooling day were developed to examine the response of the model on an hourly basis. The ambient temperature, attic temperature, cooling load, duct losses (energy and percent of load), and distribution efficiency are plotted for climate zones 3 and 12 in the Figures below:

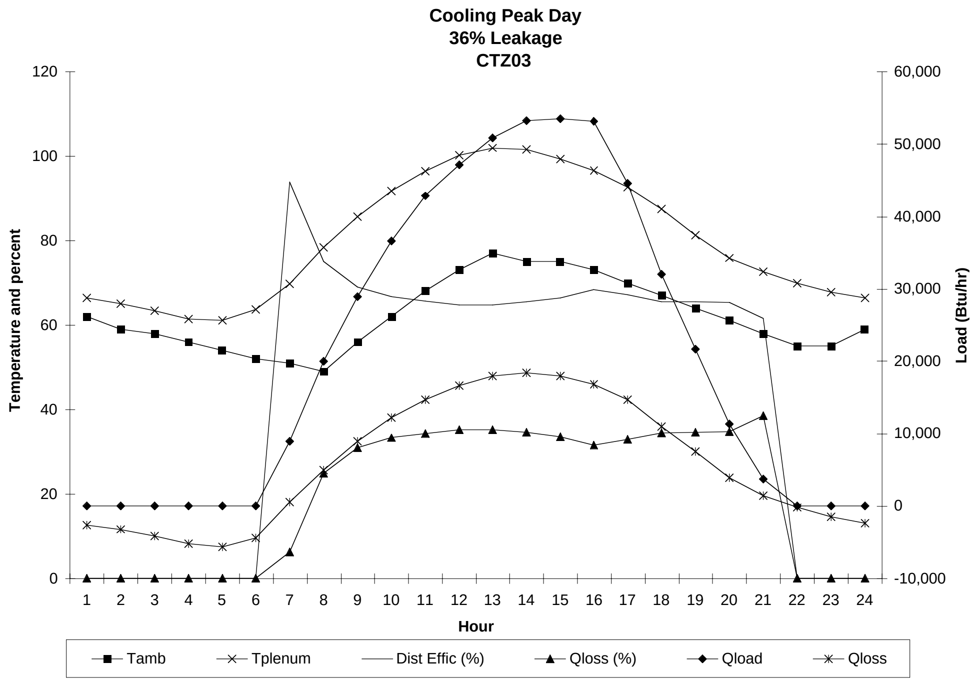

Figure A-6 Cooling Peak Day Performance, Climate Zone 3

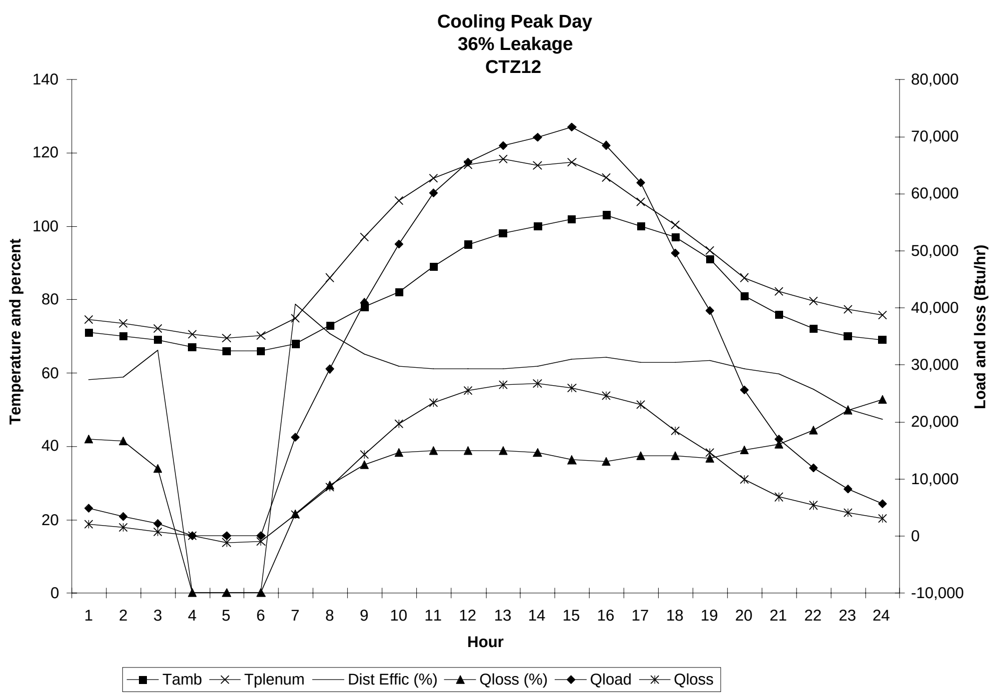

Figure A-7 Cooling Peak Day Performance, Climate Zone 12

Note, the distribution efficiency is generally not at the minimum point during the peak cooling hour, since the distribution losses expressed as a percentage of the total load are generally higher before the HVAC system "peaks." This is due partially to the time lag in the zone cooling response relative to the attic, and the unintended cooling effects of supply leakage that moderate attic temperatures during peak cooling periods.

Comparison with ASHRAE Standard 152

A series of studies were conducted to compare the results of the DOE-2.2 simulations to ASHRAE Standard 152. Changes were made to the DOE-2.2 model to better replicate the cooling loads and system response of a residential building. Efficiency calculations for several climate zones were compared as follows:

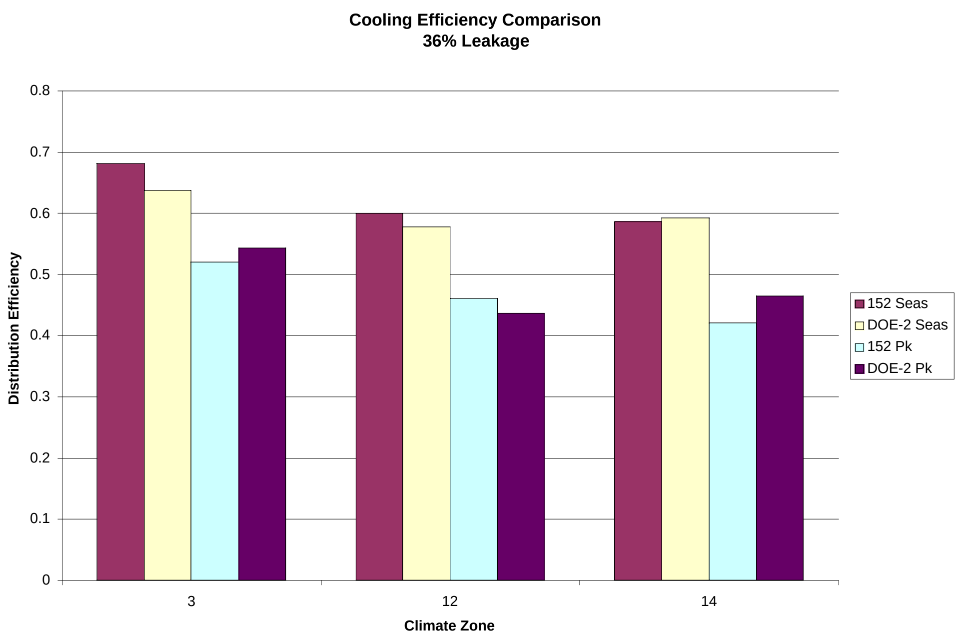

Figure A-8. Cooling Efficiency Comparison

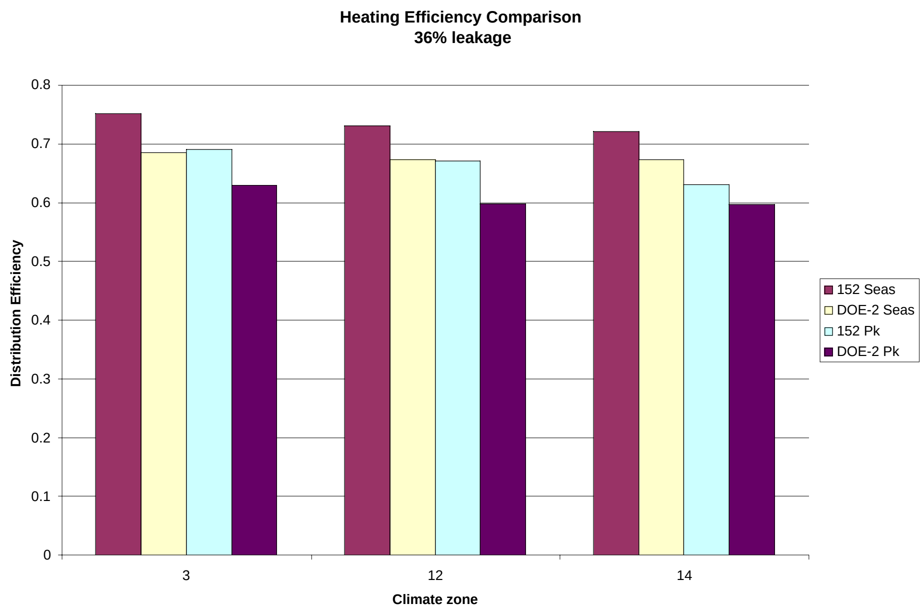

Figure A-9. Heating Efficiency Comparison

Another comparison was done to look at the energy savings on a percentage basis resulting from duct leakage sealing. This comparison is shown below:

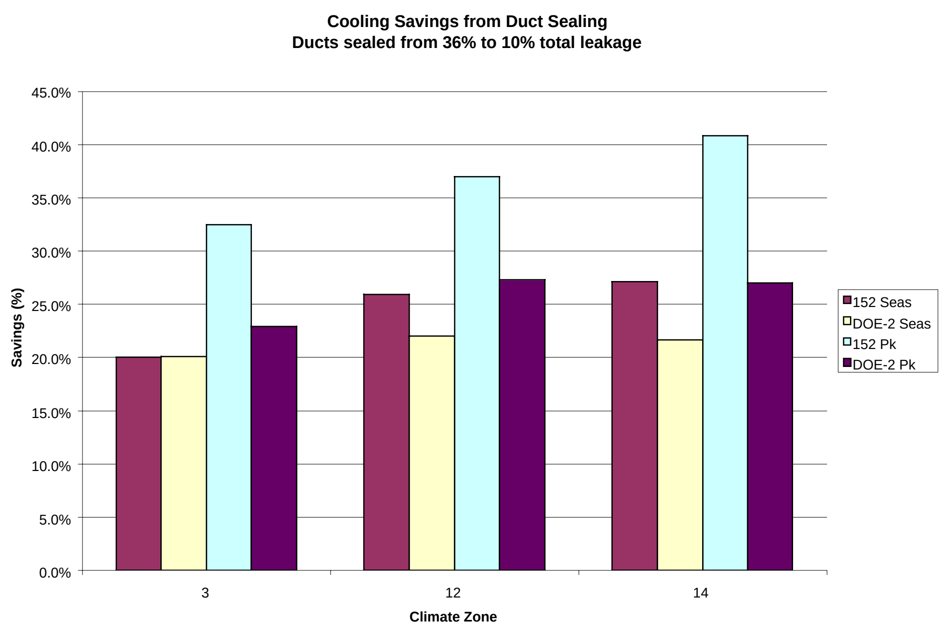

Figure A-10. Cooling Savings Comparison

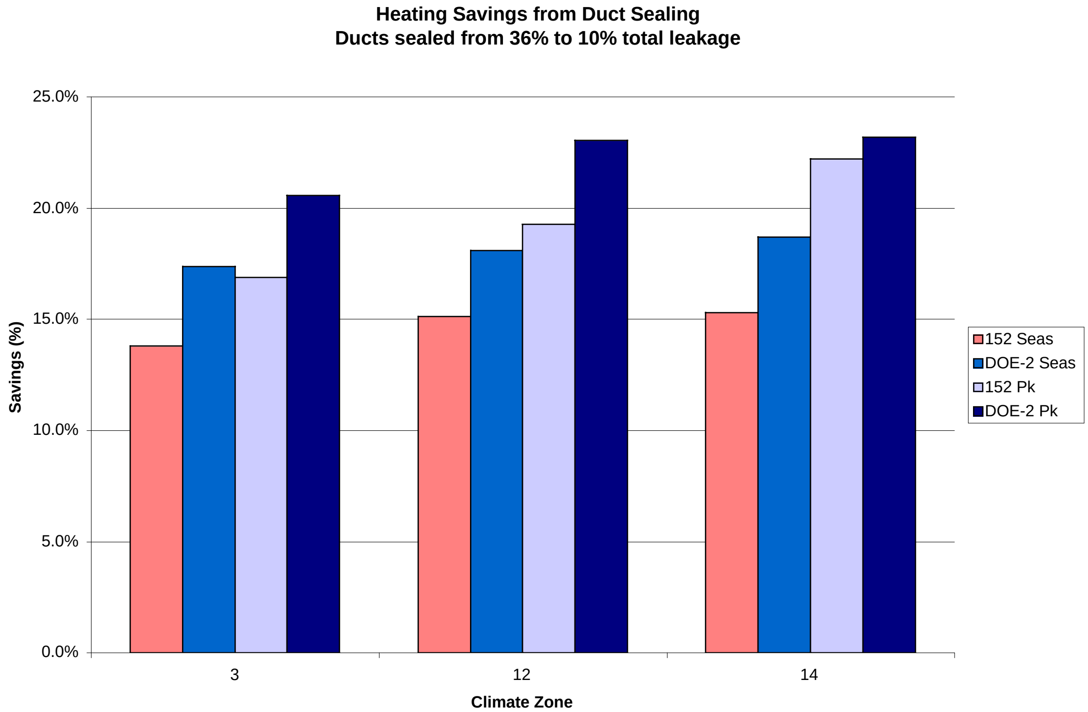

Figure A-11. Heating Savings Comparison

The two methods compared within 30% ,which is considered reasonable given the different approaches and climate data assumptions used by each method. Statistics compiled from this comparison are summarized below:

Table A-1 Distribution Efficiency Comparison

CZ	Cooling				Heating			
	152 Seas	DOE-2 Seas	152 Pk	DOE-2 Pk	152 Seas	DOE-2 Seas	152 Pk	DOE-2 Pk
3	0.850	0.797	0.770	0.703	0.870	0.829	0.830	0.792
12	0.810	0.740	0.730	0.600	0.860	0.821	0.830	0.776
14	0.804	0.755	0.710	0.636	0.850	0.826	0.810	0.776

Table A-2 Ambient Temperature Comparison

CZ	Cooling				Heating			
	152 Seas	DOE-2 Seas	152 Pk	DOE-2 Pk	152 Seas	DOE-2 Seas	152 Pk	DOE-2 Pk
3	75.1	68.2	89.0	89.0	52.2	51.1	31.0	34.0
12	84.0	79.1	100.0	102.0	48.0	47.2	26.0	27.0
14	86.3	81.1	108.0	101.0	42.7	42.2	15.0	18.0

Table A-3 Attic Temperature Comparison

CZ	Cooling				Heating			
	152 Seas	DOE-2 Seas	152 Pk	DOE-2 Pk	152 Seas	DOE-2 Seas	152 Pk	DOE-2 Pk
3	84.1	83.7	111.0	102.9	54.2	50.9	42.0	35.3
12	93.0	94.8	122.0	121.4	50.0	47.1	37.0	25.5
14	95.3	97.6	130.0	118.2	44.7	41.5	26.0	17.4

Table A-4 Ambient Humidity Ratio Comparison

CZ	Cooling			
	152 Seas	DOE-2 Seas	152 Pk	DOE-2 Pk
3	0.00928	0.00907	0.00840	0.00560
12	0.01056	0.00791	0.00880	0.01170
14	0.01024	0.00379	0.00620	0.00610

Table A-5 Attic Humidity Ratio Comparison

CZ	Cooling			
	152 Seas	DOE-2 Seas	152 Pk	DOE-2 Pk
3	0.00928	0.00891	0.00840	0.00560
12	0.01056	0.00779	0.00880	0.01088
14	0.01024	0.00379	0.00620	0.00610

Table A-6 Indoor Humidity Ratio Comparison

CZ	Cooling			
	152 Seas	DOE-2 Seas	152 Pk	DOE-2 Pk
3	0.00771	0.00708	0.00679	0.00560
12	0.00740	0.00690	0.00720	0.00750
14	0.00809	0.00379	0.00606	0.00610